Proceedings of the

Environmental Problems in Karst Terranes and Their Solutions Conference

October 28-30, 1986
Bowling Green, Kentucky

Sponsors

National Water Well Association
Eastern Kentucky University
Friends of the Karst
Kentucky Division of Water
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Published by

National Water Well Association
6375 Riverside Drive
Dublin, Ohio 43017

Produced by

Water Well Journal Publishing Company
6375 Riverside Drive
Dublin, Ohio 43017

DYE TRACING STUDIES OF THE FOUNTAIN, MINNESOTA SEWAGE SYSTEM

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Abstract

Fountain, a small community in southeastern Minnesota, is located on a sinkhole plain developed in the Ordovician Galena Formation. Many of the approximately 100 houses in the town have sewer systems that empty directly into sinkholes. Qualitative dye traces using Fluorescein and a quantitative dye trace using Rhodamine WT indicate that effluent from the community's individual disposal systems resurges at a group of springs about a mile northwest of the community. These springs are located in the Galena aquifer which comprises the upper karst above the Decorah Shale aquitard. The travel time of the underground flow here is about one day.

The citizens of Fountain are considering the construction of a community drainfield to alleviate the sewage disposal problem. The effluent from individual septic tanks would be collected and piped to a drainfield about two miles south of town. The proposed drainfield site is stratigraphically below the Decorah Shale in a valley underlain by limestones and dolomites of the Praire du Chien Group. Watson Creek, which flows through the valley, is a karst stream which loses water into the ground in the vicinity of the proposed site. The quantitative dye trace from the proposed site indicates that the water beneath it is moving southeast at a velocity of about 1.3 miles/year. Water in the lower karst aquifer (in the Prairie du Chien) is moving two to three orders of magnitude more slowly than in the upper karst aquifer (in the Galena). ^{14}C analyses of the water in the Prairie du Chien aquifer are consistent with the dye trace results and indicate residence times of less than 25 years.

Flow in the upper karst aquifer is about 300 times faster than in the lower aquifer, and in the opposite direction.

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Introduction

Fountain is a small community (population ~ 300) in Fillmore County, southeastern Minnesota. The town is situated on a broad plateau of the Ordovician Galena Formation (limestone and dolomite) in the midst of one of the densest concentrations of sinkholes in Minnesota. There is no municipal sewage treatment system. Many of the approximately 100 houses in the town have sewer systems which empty directly into sinkholes. The rest of the homes use septic tanks which ultimately discharge into the underlying karst aquifer.

For almost a decade Fountain, its consultants and state regulatory agencies have investigated alternative methods of disposal of its sewage. The current proposal (EPA, 1986) is to build a community drainfield wastewater treatment system which involves: 1) installation of a small diameter collection system for septic tank effluent to service the existing or newly installed septic tanks, 2) construction of about 2 miles of force main/gravity interceptor sewer to transport the septage, 3) 45,500 square feet of rock-filled trenches in a community drainfield, and 4) a monitoring well system around the drainfield.

This paper describes: 1) use of quantitative dye tracing to define the direction and velocity of ground water from the proposed drainfield site, 2) the significant implications of the results.

Geologic and Hydrologic Setting

Figure 1 is a map showing the area around Fountain and the proposed drainfield. The base is adapted from the USGS Fountain, Preston, Chatfield and Pilot Mound 7.5-minute topographic maps. Figure 2 shows cross sections through the area along the lines indicated in Figure 1. The cross sections are based on water well logs, field work, and information from this work about ground water flow. The surficial deposits in the area are loess, glacio-fluvial sediments, and residuum. The entire area is underlain by nearly flat-lying Ordovician sedimentary rocks. The stratigraphic nomenclature used here is that of Austin (1972).

Fountain is on a sinkhole plain that is part of a broad plateau on the Galena Formation. The Galena is underlain by the Decorah Shale, a local aquitard which crops out around the edges of the plateau. Three major springs, northwest of Fountain, Cave Spring, Quarry Spring, and Little Quarry Spring, emerge just above the Galena/Decorah contact. The Decorah is underlain by the Platteville Limestone, Glenwood Shale and St. Peter Sandstone. These three formations also crop out along the sides of the plateau.

The proposed drainfield site is on the edge of a broad valley about 2 miles south of Fountain and about 200 feet lower in elevation. The site is underlain by the limestones and dolomites of the Prairie du Chien Group. Watson Creek flows east through the valley and is a losing stream in the vicinity of the proposed drainfield. The regional base level is

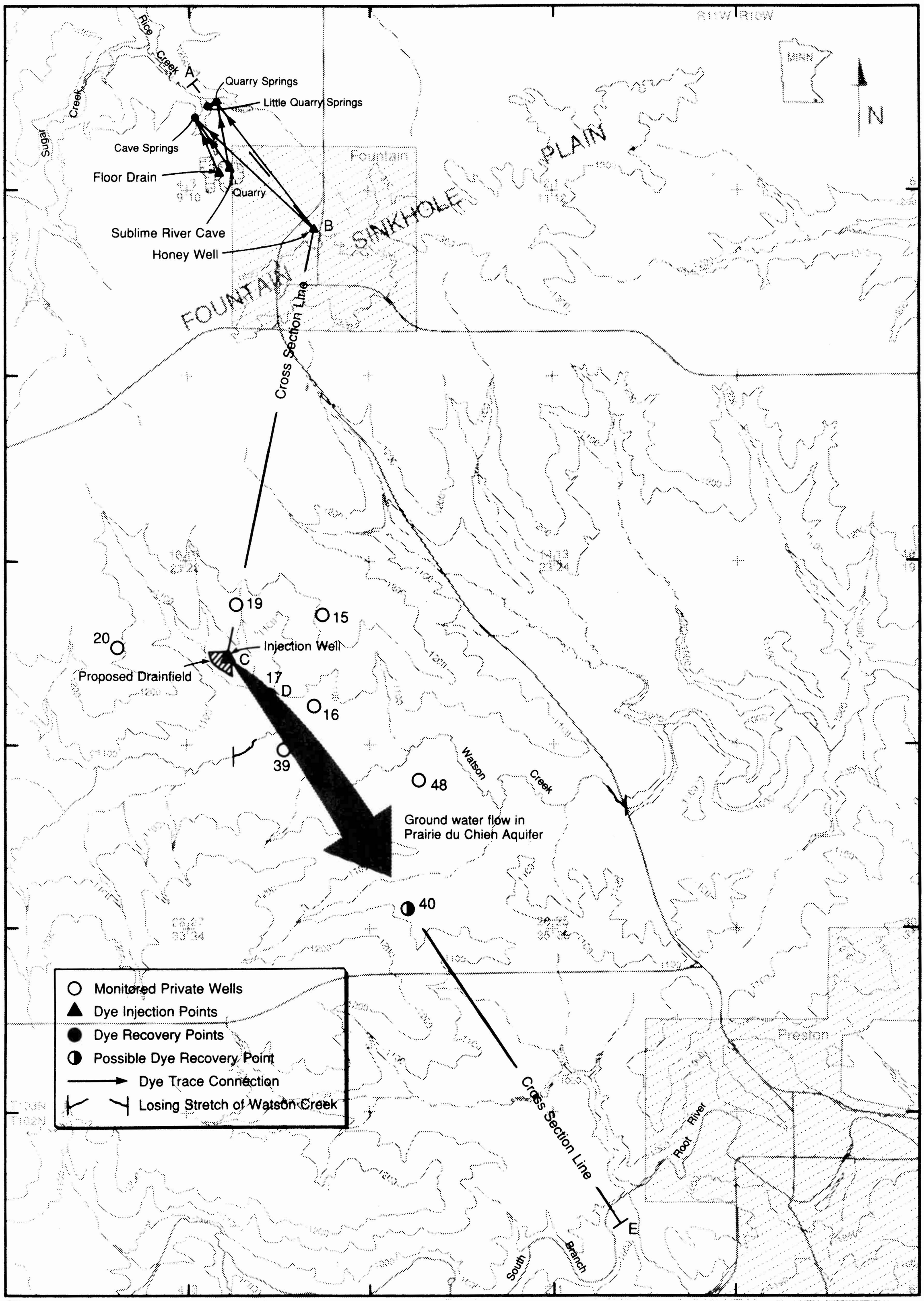

Figure 1. Map of Fountain and surrounding area. Ticks indicate section corners and are one mile apart.

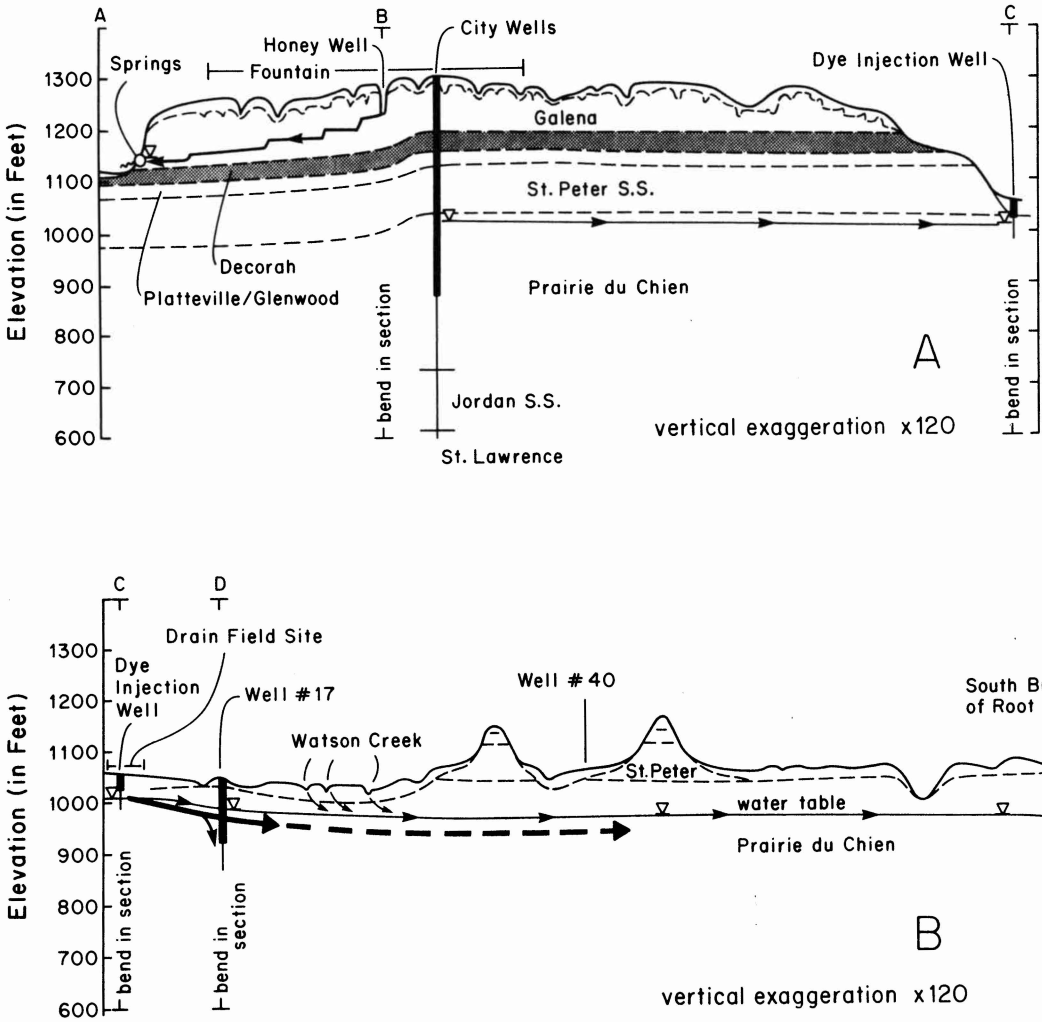

Figure 2. Cross sections along the line shown in Figure 1. Figure 2A extends from the springs northwest of Fountain to the drainfield site. Figure 2B extends from the drainfield southeast to the South Branch of the Root River.

the South Branch of the Root River which is located beyond a ridge and about 3.5 miles south of the proposed drainfield.

In 1978 Ron Spong, Ramesh Venkatakrishnan, Ted Marshall, and Rick Cunningham made three qualitative dye traces in and around Fountain (Ron Spong, written communication, 1978). In separate traces, Fluorescein was injected at two locations in the bottom of Kapper's Quarry (Floor Drain and Sublime River Cave) and in Honey Well, a dry well that receives septage from seven households, in Fountain. These features are shown in Figure 1. The Fluorescein was detected visually and with charcoal "bugs" in Cave Spring, Quarry Spring and Little Quarry Spring. The dye typically arrived at the springs less than one day after injection.

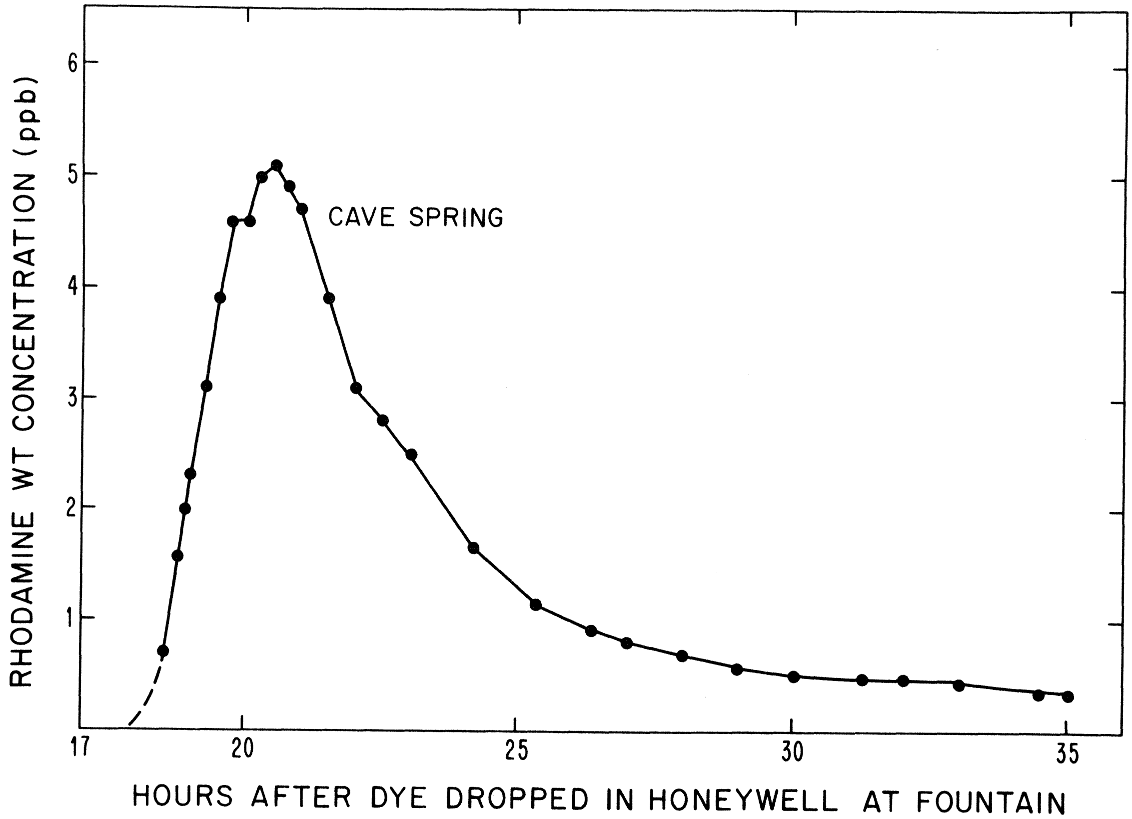

Figure 3. Breakthrough (curve dye concentration vs. time) for a dye trace by Eric Mohring, from Honey Well to Cave Spring. A slug of 456 g of Rhodamine WT 20% solution was injected at Honey Well. Grab samples of water were collected at Cave Spring, Quarry Spring and Little Quarry Spring. Dye was detected only at Big Spring. The lack of dye recovery at Quarry and Little Quarry Springs can be due to either too short a sampling period or low flow conditions.

These traces were confirmed in October 1980 by using Rhodamine WT and fluorometric analysis of grab samples (Eric Mohring, written communication, 1980). Figure 3 shows that the peak of the breakthrough curve arrived at Cave Spring about 20 hours after dye injection. Both the qualitative tracings and quantitative tracing indicate that septage which enters the Galena aquifer under Fountain resurges at the three large springs northwest of town. The underground residence time is about a day. These subsurface flow paths are indicated in Figure 1 and Figure 2A.

Regional Water Quality

As part of the background study for the Fountain drainfield project, residential wells within a 2-mile radius of the proposed site were sampled and analyzed for nitrate content. Nitrates are a sensitive and useful indicator of overall water quality. The drinking water standard for nitrate-nitrogen is set at 10 ppm (EPA, 1975). Elevated nitrate levels are frequently caused by contamination from manure, domestic wastewater, or chemical fertilizers. Thirty-six wells were sampled and analyzed in December, 1983, and again in May, 1984. Although detailed information on depth and construction of all of the wells is not available, the majority of the wells produce water from the Prairie du Chien/Jordan aquifer.

Three conclusions can be drawn from the nitrate data. First, water quality varies widely in the study area; nitrate-nitrogen content ranges from <0.1 ppm to more than 50 ppm. Second, there is no significant trend in the change in nitrate levels in the same well between the two samplings; 19 wells showed a decrease (improvement) in nitrates from December, 1983, to May, 1984, 15 showed an increase (deterioration) and 2 showed no change. Third, and most significant, 47%, nearly half the wells sampled, showed nitrate-nitrogen levels which exceed the drinking water standard of 10 ppm. Six of the seven wells used in the dye trace study discussed below exceeded the standard in at least one of the samplings. The drinking water supply (the Prairie du Chien/Jordan aquifer) in this area is already seriously threatened by contamination from human activities. The ability of this ground water system to absorb and to dilute nitrates to acceptable levels is therefore greatly limited.

As part of a survey of southeastern Minnesota ground water for pathogenic viruses, S.M. Goyal of the University of Minnesota College of Veterinary Medicine sampled Cave Spring seven times between July 25, 1985 and January 2, 1986. All of the samples contained numerous coliform bacteria, and five of the seven samples contained fecal coliforms. One sample contained the coxsackie virus B-2 which causes pleurodynia, myalgia, myocardial infarctions and respiratory infections (S.M. Goyal, written communication, 1986). Dr. Goyal's results clearly show that human pathogens are reaching the Galena karst aquifer beneath Fountain.

Quantitative Dye Tracing from Proposed Drainfield

The goal of our dye trace was to determine the direction and velocity of groundwater flow beneath the proposed drainfield site and to identify any hydrologic connections between the drainfield and private wells in the immediate vicinity. Seven private wells (numbers 15, 16, 17, 19, 20, 39 and 48) were selected as sampling stations. Locations of these wells are shown in Figure 1. They were selected on the basis of their proximity to the drainfield site as well as the ability and willingness of the owners to participate in the study by taking daily water samples.

A dye-injection well was drilled in the northeast corner of the drainfield site in January of 1984. The well penetrated 26 feet of unconsolidated material and 41 feet of Shakopee Dolomite (upper Prairie du

Chien) to a total depth of 67 feet. The well was cased with 4-inch casing to a depth of 29 feet, leaving 38 feet of open hole in the Shakopee Dolomite. Water was encountered at 41 feet; the bottom 26 feet of the hole were full of water.

Participants in the study began taking daily water samples on January 31, 1984, 12 days prior to injection of the dye. These samples were analyzed to determine the natural background fluorescence of the water. On February 12, 1984, 10 lbs of Rhodamine WT dye (50 lbs of 20% solution) was poured into the injection hole. An additional 500 gallons of water was pumped into the well from a Fountain municipal fire truck to help inject the dye into the bedrock. The well pipe did not fill at any time during the approximately 30 minutes of pumping, indicating that the well accepted water at a rate of at least 1000 gallons per hour.

Water samples were collected once daily by the seven participants from January 31 to June 15, 1984. The sampling of four wells (numbers 15, 16, 17 and 39) was extended through mid September, 1984. All samples were analyzed for Rhodamine WT at the University of Minnesota using a Turner Designs Model 10-005 Fluorometer. The data obtained from these analyses are shown in Figures 4 and 5. The background level of fluorescence in the

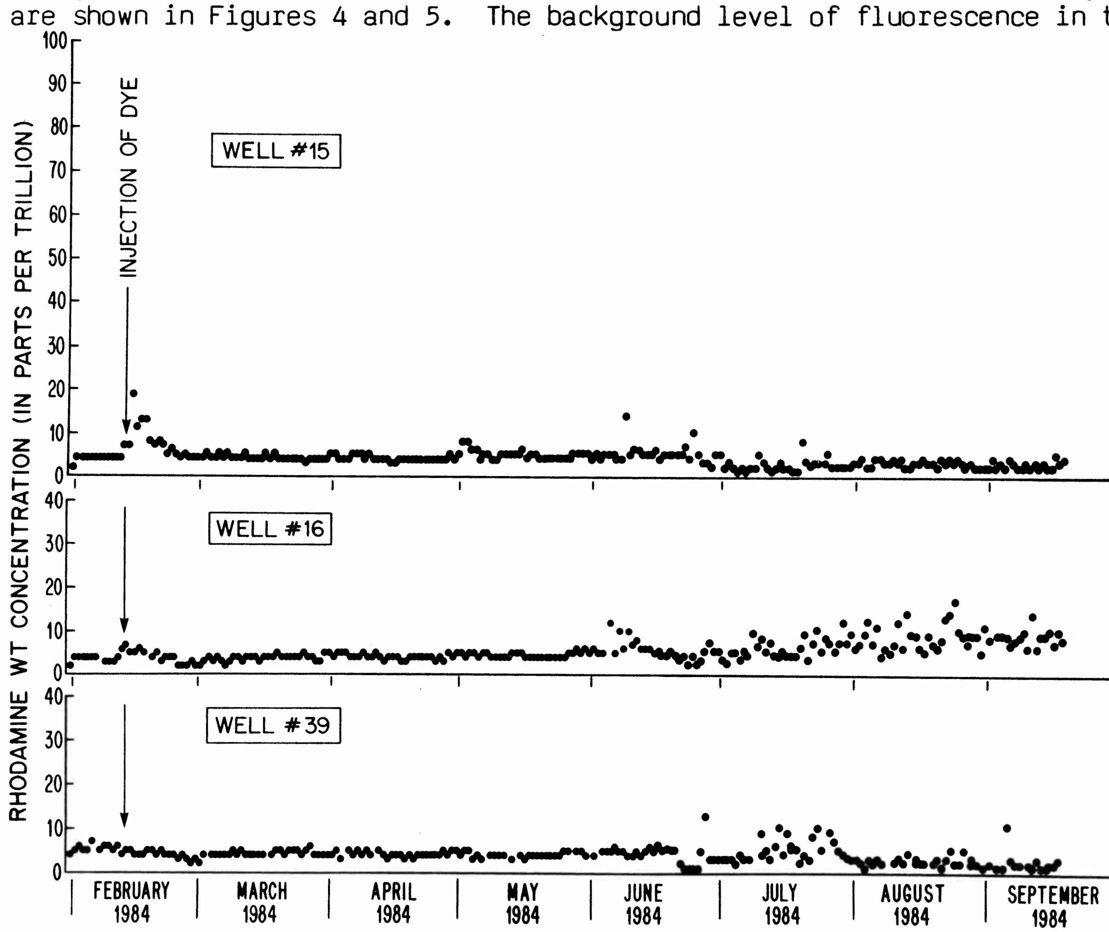

Figure 4. Plot of background fluorescence vs. time at three wells. The fluorescence is reported as equivalent Rhodamine WT concentrations but no dye was detected. Each dot is from a water sample collected by the well owner.

samples ranged from about 2 to 10 (usually 3 to 5) parts per trillion (ppt). In six of the seven wells, no pulses significantly above background levels were detected during the sampling period from January 31 to mid-September, 1984. Figure 4 illustrates the data from three of these wells. Data from the other wells numbers 19, 20 and 48, for which sampling was terminated on June 15, 1984 are very similar to that shown in Figure 4.

One well, #17, began to show a positive dye pulse on April 21, 1984, 10 weeks after the dye injection. These data are shown in Figure 5. The fluorescence at the Rhodamine WT emission band, and by inference, the concentration of dye, rose steadily from a background level of about 5 ppt to a peak of 166 ppt on May 29, 1984. It then gradually dropped to background levels early in July, 1984. A second pulse of dye began to emerge from the well and reached a peak value of 26 ppt in late July. When sampling was terminated in mid-September the concentrations from well #17 had returned to background levels.

Well #17, 186 feet deep, was drilled in 1978. It was properly cased and grouted to a depth of 130 feet. Although casing and grouting may protect a well from contamination by pollution sources immediately around the wellhead, such construction techiques offer no protection from pollutants with in the aquifer itself.

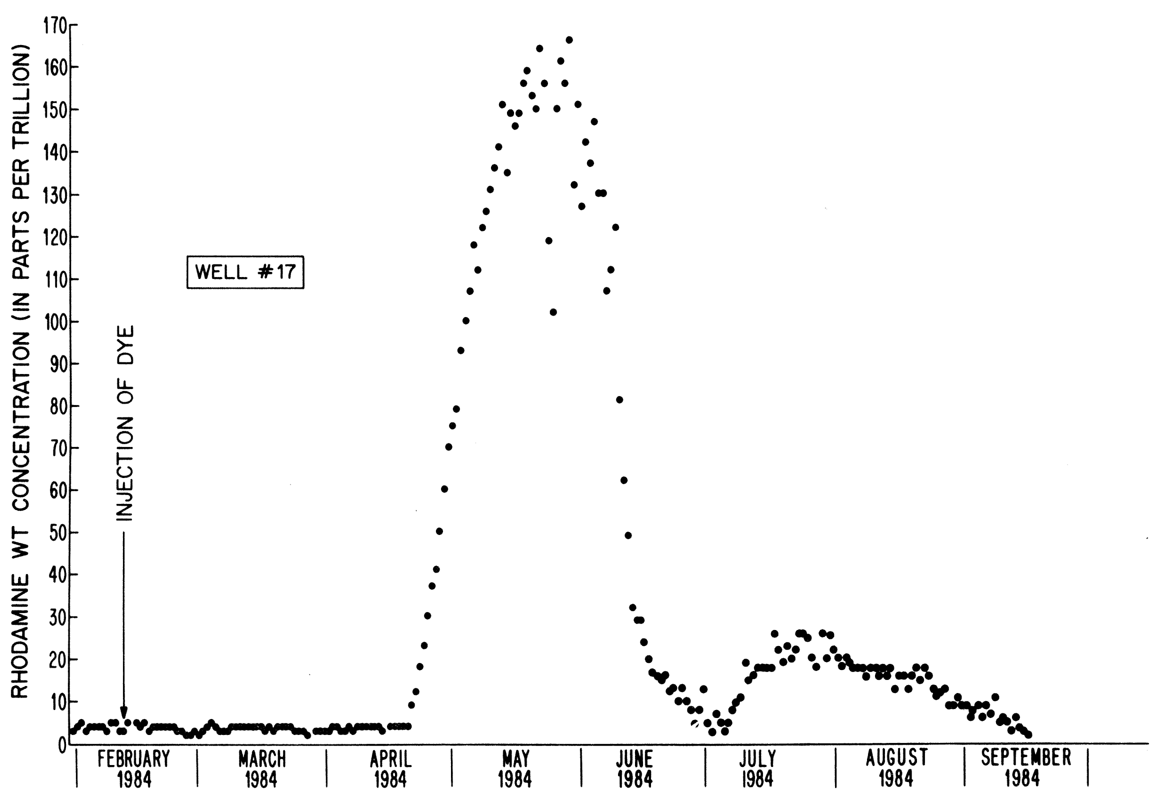

Figure 5. Rhodamine WT breakthrough curve for Well #17. Each dot is from a water sample collected by the well owner.

Water samples from Well #17 were tested to confirm that the observed fluorescence was due to the presence of Rhodamine WT. This test is based on the fact that the fluorescence of Rhodamine WT has a unique and measurable temperature dependence. A plot of the fluorescence of a water sample vs. temperature, and a comparison with a similar plot of a known Rhodamine WT standard can be used to distinguish this dye from most other fluorescent materials. If the slopes are parallel, i.e., if the thermal coefficients of fluorescence are equal, the unknown is taken to be Rhodamine WT (Dalgleish and Alexander, 1984). The temperature coefficient of the fluorescent material in samples from Well #17 is identical to that of Rhodamine WT.

Well #17 is located 1/4 mile southeast of the injection well; the leading edge of the dye-pulse reached it in 10 weeks. Assuming this flow rate is representative groundwater beneath the drainfield flows toward the southeast at about 1.3 miles/year.

Dye Trace Postscript

In late February, 1986 word reached us that the water in well #40 (shown in Fig. 1) had turned visibly red in the summer of 1985 -- more than a year after the dye had been injected -- and that a sample of the red water might have been "preserved" in a stock-watering trough that had not been used since the preceeding summer. On March 6, 1986 the senior author visited the site and collected samples of water from the well and three different types of sample from the stock trough (an old porcelain bath tub). The trough was ringed and lined with algae and "scum" of the type commonly found in stock watering troughs and it contained bits of hay and other organic debris. The water in the trough had been frozen during most of the winter but was partially thawed when sampled. Samples were collected of the water itself, the water plus some of the algae which was growing below the water line on the sides of the trough, and the water plus a reddish "scum" which was revealed when the algae was scraped off the edge of the tub. Water was also collected from the domestic water supply.

The samples collected from the well contained very little fluorescent material, < 2 ppt, and give no indication that any Rhodamine WT was in the well as of March, 1986. All three samples from the trough contained detectable fluorescent material. The fluorescent material in the water and the water plus the algae did not, however, pass the temperature test described above and did not appear to be Rhodamine WT. The samples of water plus reddish "scum" yielded an intermediate temperature test, i.e. it behaved as though a 103 ppt value read by the fluorometer was a mixture of Rhodamine WT and the unknown fluorescent material in the other two samples.

Although the "chain-of-custody" for these samples is non-existant, the results are consistent with the flow direction and velocity revealed by the regular portion of the dye trace and with the regional water table data. Well #40 is therefore indicated in Figure 1 as a possible dye recovery point.

Carbon-14 Age Determinations and Isotopic Analysis

As part of our study we selected three wells, #16, #19 and #48, for ^{14}C, $\delta^{13}C$, $\delta^{18}O$ and δD analyses. These wells were selected because they were thought to be wells which would be sampling the shallowest aquifer.

About 200 liters of water were collected from each water system in a barrel lined with a large polyethylene bag. The pH of the water was raised to ~ 10 by adding NH_4OH. $BaCl_2$ was added to the water to precipitate the carbonate as $BaCO_3$. After the $BaCO_3$ had settled to the bottom, the supernatant was siphoned off and the $BaCO_3$ transferred to the laboratory at the University of Minnesota. The $BaCO_3$ was then repackaged and shipped to Beta Analytic Inc., Coral Gables, Florida, for analysis. The ^{14}C and $\delta^{13}C$ data are shown in Table 1.

Small, ~ 100 ml, samples of the water were collected as the barrels were being filled. These samples, with no chemicals added, were submitted to Global Geochemistry Corp., Canoga Park, California, for $\delta^{18}O$ and δD determinations. These data are also shown in Table 1.

The measured ^{14}C content of each carbonate sample was corrected for "dead", limestone carbonate based on the $\delta^{13}C$ content of the sample under the assumption that limestone carbonate has a $\delta^{13}C = 0$ while biogenic carbon dioxide has a $\delta^{13}C = -25$. The resulting "^{14}C corrected" values were then compared with the known fluctuation of ^{14}C in the earth's

Table 1. Isotope Data

Well	^{14}C (1.)	$\delta^{13}C$ (2.)	$^{14}C_{corr}$ (3.)	$\delta^{18}O$ (4.)	δD (5.)
#16	0.957 ±0.007	-21.05	1.137 ±0.008	-9.48	-60, -59
#19	0.775 ±0.007	-13.27	1.460 ±0.013	-10.05	-64, -65
#48	0.911 ±0.008	-21.89	1.040 ±0.009	-9.44, -9.42	-60

Notes:

1. In units of fraction of modern ^{14}C.
2. In units of per mil (parts per thousand) relative to the PDB-1 standard.
3. In units of fraction of modern ^{14}C. $^{14}C_{corr} = {}^{14}C/(\delta^{13}C/-25.00)$.
4. In units of per mil relative to SMOW.
5. In units of per mil relative to SMOW.

biosphere/atmosphere. All three values are greater than modern (1950 AD) ^{14}C value, which indicates that the water in each of these three wells entered the ground after the advent of atmospheric nuclear weapons testing. The $\delta^{18}O$ and δD values all plot near a "meteoric water line" and give no indication of equilibration with the aquifer matrix.

Discussion

The 1978 qualitative Fluorescein traces and the 1980 quantitative Rhodamine WT trace clearly show that water infiltrating into the Galena karst aquifer beneath Fountain resurges at Cave, Quarry and Little Quarry Springs. The transit time for the dye is about one day. Dr. Goyal's work clearly indicates that the waters of Cave Spring are contaminated with human pathogens.

The nitrate survey of existing wells around the proposed drainfield site clearly documents that water in the Prairie du Chien/Jordan aquifer is already severely stressed. The quantitative Rhodamine WT dye trace indicates that ground water beneath the proposed drainfield is moving southeast at a velocity of about 1 mile per year. Watson Creek appears to be perched above, and loses water to a regional flow system which probably discharges in the South Branch of the Root River, near Preston.

Although the data from well #40 are impossible to document adequately, the observation that the water was visibly pink indicates a dye concentration of 10 to 20 parts per billion which is about 100 times more concentrated than was observed at Well #17. There is no reason to believe that either well happened to intersect the main solution conduit draining the proposed site, indeed it would be exceedingly fortuitous if either of them did so (Quinlan and Ewers, 1985, p. 209-210).

The isotopic data are consistent with a ground water residence time of less than 25 years in the Prairie du Chien aquifer in the vicinity of the proposed drainfield.

The primary hydrogeologic observation is that ground water in the upper karst aquifer is moving at a radically different velocity than is water in the lower karst aquifer. Ground water velocity in the relatively maturely karsted Galena aquifer is about a mile per day. Ground water velocity in the less maturely karsted Prairie du Chien aquifer is about a mile per year. The opposite directions of flow are probably due to a ground water divide in the system. This study is therefore one more illustration of the extreme heterogeneity of karst aquifers on even a local scale.

The primary methodological observation is that quantitative dye tracing using Rhodamine WT can be successfully used to trace flows to private wells in systems with ground water flow velocities of as little as a mile per year. The dye trace was terminated, partly for economic reasons, before the full extent of the southeastward flow path was demonstrated. In the future, such dye traces should be anticipated to last for several years.

Observations

The current sewage disposal situation at Fountain results in raw sewage contaminating the Galena aquifer. The town of Fountain, its consultants, and the state regulatory agencies acknowledge this and are searching for a remedy.

Unfortunately, the currently proposed project will also adversely affect an important aquifer which is used much more heavily than the Galena aquifer. It is impossible, however, to completely quantify that adverse impact at this time. As currently planned, the drainfield project will replace wells number 17, 16 and 39 (but not 40) with new wells cased and grouted into the Franconia aquifer (Johnson, 1986). While this should alleviate the impact on the three closest, down-gradient domestic wells, well-replacement ignores the real problem -- drainfields have never been shown to work in an environmentally acceptable manner in karst regions. We are aware of no scientific work, by people experienced in karst hydrology, which demonstrates that drainfields of the scale of this proposed project adequately protect the underlying ground water. On the contrary, clear evidence exists that drainfields in karst regions can act as devices to pour effluent into the ground water. For example, Crawford (1986) convincingly shows that dye injected into a new, carefully constructed drainfield started emerging in a spring 0.8 mile away in only 10 hours. This test was run at Bowling Green, Kentucky, where the karst development is more mature than is present near the proposed Fountain drainfield. However, abundant anecdotal evidence of ground water pollution by individual scale drainfields in southeastern Minnesota karst exists.

The planning process leading to the current drainfield proposal has examined variations of seven different wastewater management alternatives (EPA, 1986). Only one of these alternatives, regionalization with the Preston Sewage Treatment Facility, completely avoids impact on ground water aquifers. (The effluent from the Preston Facility is discharged into the South Branch of the Root River at a point where the discharge remains part of the surface flow.) The capital costs of the regionalization and drainfield concepts are similar but regulatory interpretations of the fraction of each option which could be cost-shared under federal and state grants can double or triple the final local costs. This makes the environmentally unsound alternative the most economically attractive alternative -- at least for the short term. The economics of this situation are being controlled by bureaucratic regulations that seem incapable of recognizing the realities of karst hydrology.

Acknowledgements

This work was supported in part under grant C271047-02 to Fountain. from the U.S. EPA via McGhie and Betts, Inc., Rochester, Minn. and in part under a grant from the Legislative Commission on Minnesota Resources. Special thanks are due to the local citizens who faithfully collected water samples for the project and Vern Spelhaug, Fountain Water Superintendant, who shipped the water samples to us weekly. We gratefully acknowledge the use of unpublished tracing results from Ron Spong, Eric Mohring and unpublished pathogen data from Sagar Goyal.

This is Publication No. 1104 of the School of Earth Sciences, Department of Geology and Geophysics of the University of Minnesota.

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Biographical Sketches

E. Calvin Alexander, Jr. is an Associate Professor in the Department of Geology and Geophysics at the University of Minnesota. He is interested in karst environmental geology, ground water flow in fractured aquifers, pollution by non-point sources, geochronology, and isotope geology.

Jodi A. Milske is a consulting hydrogeologist with HDR Techserv, in Minneapolis. She specializes in environmental impact assessment, solid waste disposal facilities, and landfill siting. Her graduate work involved karst hydrogeology and cave sediment analysis.

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Questions and Answers

Question: What was used to analyze your Rhodamine WT samples?
Answer: A Turner Designs Model 10-005 filter fluorometer. The samples are all grab samples collected in 8 dram, screw cap vials which fit directly into the fluorometer. Each sample is preserved in its own vial and can be reanalyzed at a later date and/or subjected to the temperature test described in the text.

Question: Does Rhodamine WT evaporate with evaporating water? If not, couldn't the high concentration of Rhodamine in the stored bath tub water be a result of significant evaporation (prior to freezing) causing an anomalous enrichment of the tracer?
Answer: Rhodamine WT does not, to my knowledge, evaporate. Such a concentration mechanism is possible. Any such concentration would probably have been lost to the more probable adsorption and decomposition losses over the intervening months. The point is academic, however. The concentrations in the trough in March, 1986 were low. The inferred high concentrations are based on the report of visible pink color during the summer of 1985.